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Geospatial Mapping of Groundwater Contamination Vulnerability in Lagos Mainland, Lagos State

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ABSTRACT

The rapid urbanization of recent years has led to a surge in urban population, driving up the demand for water resources. This has taken a toll on groundwater, both in terms of quantity and quality. Anthropogenic activities, change in land use, and changes in topography have rendered groundwater highly susceptible to contamination. To ensure sustainable water utilization, a robust water management system is essential. This study focuses on assessing groundwater vulnerability to pollution in Mainland Local Government Area (LGA) of Lagos, a region grappling with urbanization challenges. We utilized geological and hydrogeological data from existing sources and collected spatial data, including borehole coordinates, road networks, river locations, topographical features, and geological data, which were organized into a geodatabase for geospatial analysis. Our approach involved the DRASTIC model, accounting for aquifer parameters like depth to water, net recharge, aquifer characteristics, Vadose zone influence, and hydraulic conductivity. This model was used to create groundwater vulnerability and risk maps, validated using groundwater quality data. The results revealed diverse susceptibility levels within Mainland Lagos, with about 18% displaying high susceptibility, 25% moderate susceptibility, 28% low susceptibility, and 29% very low susceptibility to contamination. These maps offer vital insights for informed decision-making in water resource management. By enabling sustainable aquifer use, this study sets a precedent for resource preservation amid urbanization's challenges.

Keywords: Groundwater, susceptibility, DRASTIC model, groundwater quality

1.0. Introduction

Groundwater water contamination is an increasing water resource problem globally (Dale Van Stempvoortl *et al.*, 1993). The increasing demand for its use due to rapid growth of population and the accelerated pace of industrialization has led to its constant exposure to contamination (Amadi *et al.*, 2012). Improper waste disposal among other human activities and companies' effluent discharge into the waterbody (ocean and lagoon) have all contributed to groundwater pollution. It is important to note that the natural environment is expected to provide protection for groundwater against contamination (Napolitano, 1995). However, groundwater aquifers are susceptible to contamination by activities at the land surface making groundwater quality to deteriorate. And the level of susceptibility differs based on the nature, type and volume of activities within the location. Consequently, some land areas are more vulnerable to groundwater contamination than others (Ali *et al.*, 2006). Groundwater susceptibility mapping is the measurement of the risks placed upon the groundwater by human activities and other contaminants within the environment. Without the presence of these contaminants, even the most susceptible groundwater is not at risk, and thus is not vulnerable. Hence, the area is subdivided into several hydrogeological units with different levels of vulnerability based on the rankings of the mapped natural and anthropogenic factors within the whole area. The result of the mapping exercise is known as vulnerability or susceptibility map, which shows the distribution of highly vulnerable areas as risk areas, in which pollution is very common because contaminants can reach the groundwater within a very short time (Ali *et al.*, 2006).

This study aims to assess groundwater contamination vulnerability in Mainland Local Government Area (LGA) of Lagos using the integration of DRASTIC and Geographic Information System (GIS) techniques. This model is adopted because of the availability of its required inputs and its effectiveness in measuring how easy or hard it is for contamination to reach groundwater aquifer. It is based on seven parameters to be determined as input for computing the DRASTIC index number, which reflects the contamination potential for the groundwater aquifer (Aller *et al.*, 1987). This study is necessary because of Lagos Mainland is a low land, its coastal plain-sand aquifer is characterized by shallow water table, high porosity and permeability, which makes the aquifer vulnerable qualitatively and prolific quantitatively.

Groundwater contamination involves both natural and anthropogenic factors with conflicting interests. The index and overlay method of DRASTIC modelling was employed in this study to assess these factors. This method is based on assembling relevant information of the various factors affecting groundwater contamination (Neha, 2014). The factors are interpreted by scoring, integrating, and classifying to produce an index, rank or class of "vulnerability". The method is the most suitable for integration with Geographic Information Systems (GIS), because it provides relatively simple algorithms to integrate a large amount of spatial information into maps of simple vulnerability or indices and also allows for suitable GIS analysis of all the spatial information generated (Voudouris *et al.*, 2010).

The factors considered in this study are gathered from existing literature for the building of the DRASTIC model indices (Ali *et al.*, 2006; Aller *et al.*, 1987; Napolitano, 1995), analysed and explained.

2.0 Methodology

2.1 Description of the Study Area

Lagos Mainland Local Government Area (LGA) of Lagos State is used as a case study for this research. It is located in the central part of the Sate approximately between Northings 715000mN and 723000mN and Eastings 539000mE and 544000mE. It is bounded on the west by Surulere LGA while the eastern boundary is adjacent to the Lagos Lagoon (Figure 1). Its northern and southern boundaries are shared with Shomolu and Apapa LGAs respectively. It has a total area of 20.162 km^2 about 2 percent of which is water. It is one of the smallest Local Government Area in the State.
Lagos mainland is one of the most populous Local Government Area in Lagos State, and among the state's industrialized province with a lot of business activities. Due to the presence of major markets and other institutions such as schools, hospitals, among others, the population has increased enormously and the demand for safe water by individuals and industries has also increased. The area has a good groundwater potential, and as a result, boreholes are common leading to high rate of groundwater abstraction which may pose a serious pressure on groundwater resources if unchecked

(Nwankwoala and Shalokpe, 2008). Apart from its overexploitation, its quality can also be affected due to improper waste disposal (Amadi, 2010; Amadi et al., 2012).

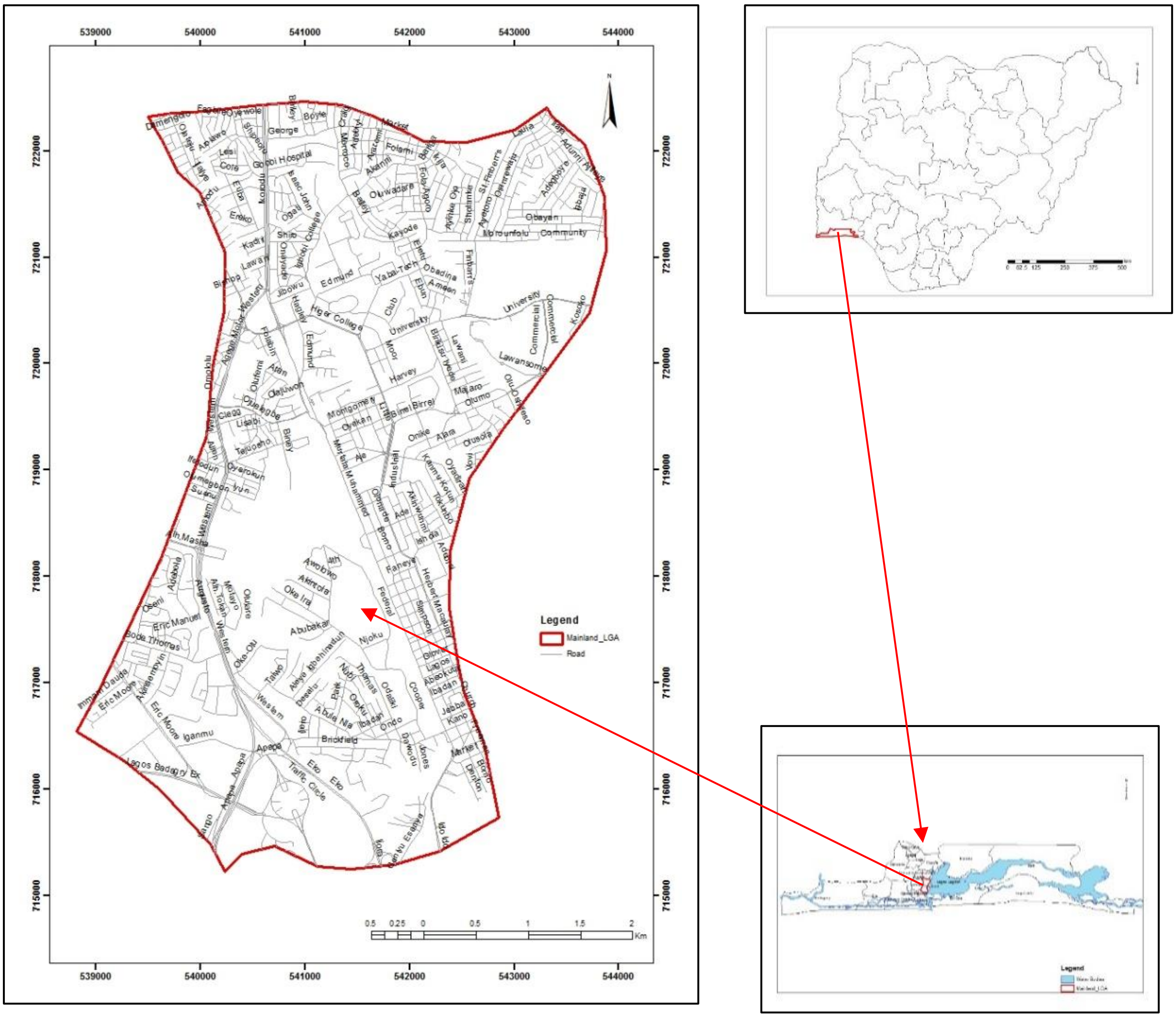

Figure 1: Map of the study area

2.2 Geological Setting of the Study Area

The geological setting of the study area lies within the extensive Dahomey Geological basin of West Africa, the low-lying basin extending almost from Accra to Lagos. The area is a sedimentary basin whose thickness increases from north to south (down dip) and from east to west. The littoral and lagoon deposit of recent sediment underlies the area. The continental basin is not too extensive, and the seabed steep away relatively steeply from onshore (Nton, 2001). Also, the study area consist of sediments of clay, unconsolidated sands and mud with a varying proportion of vegetable matter along the coastal areas while the alluvial deposit consists of coarse claying unsorted sand with clay lenses and occasional pebble beds (Alabi *et al.*, 2010).

2.3 The Borehole Sampling Locations

The sampling area selected from the study area consists mainly of boreholes drilled by the Lagos State Government for the purpose of water supply and convenience in the communities. A total of 71 boreholes were sampled from different communities in Lagos Mainland LGA State. The distributions of sampled boreholes are closely clustered as shown in Figure 2.

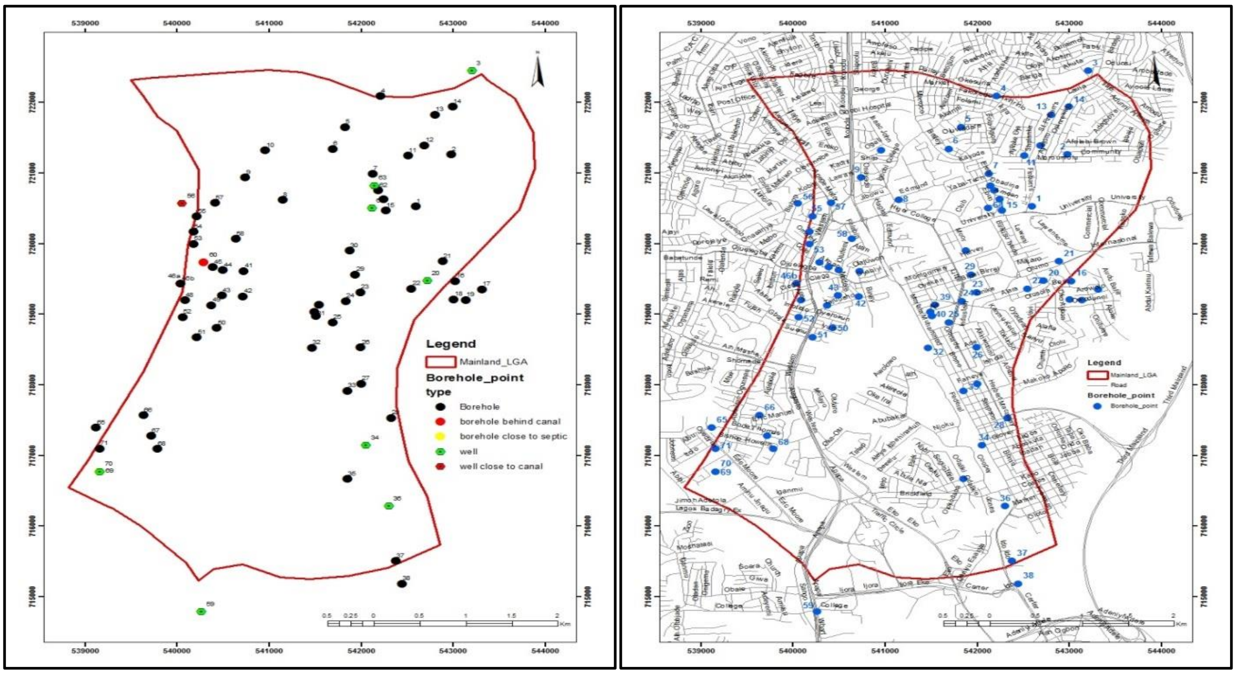

Figure 2: Sampling locations

2.4 Procedure for DRASTIC implementation

The framework adopted for this study is summarized in Figure 3. The processes include identifying the spatial and non-spatial data about the natural and anthropogenic factors that affect groundwater contamination and the structuring of these factors into the chosen model based on previous works and the peculiarity of the study area (Soladoye and Ajibade, 2014).

The index and overlay method of DRASTIC modelling was employed in this study. The method is based on assembling relevant information of the various factors affecting groundwater vulnerability. These factors are interpreted by scoring, integrating, and classifying to produce an index, rank or class of “vulnerability”. The method is suitable for integration with GIS, because it provides relatively simple algorithms to integrate a large amount of spatial information into maps of simple vulnerability or indices and also allows for suitable GIS analysis of all the spatial information generated.

After the factors were identified and structured into the DRASTIC model, the priorities of each factor were considered based on the model requirements to generate the level of vulnerability. The primary data was collected through field observation with the use of GPS. The coordinates of boreholes within the study area were collected and integrated into the GIS environment. The secondary data used for the vulnerability mapping process includes Google Earth image, geologic map, drainage pattern map, waterbodies/rivers, slope, topographical information, Landsat imagery covering the study area. The Landsat 8 satellite imagery with 30m resolution of the study area was classified and analysed in order to extract land use land cover and other relevant geospatial information within the study area. The various spatial and non-spatial data and parameters involving the mapping process were stored in a geodatabase created in ArcGIS 10.4 environment.

To generate the susceptibility map, the index model was created with ArcGIS model builder. The Landsat 8 imageries covering the whole of the study area was mosaicked and processed using Envi 5.0 software. The mosaicked image was classified to get a Land Use/Land Cover of 4 classes (Built up, Bare land, Waterbody and Vegetation) based on the considered factors. A digital elevation model (DEM) was obtained from the downloaded SRTM data and a slope model over the area was derived from the DEM. The GIS Data Layers shown in Tables 2 and 3 was used to develop a geodatabase for spatial integration of the DRASTIC model and GIS. Each layer represents the considered spatial factor based on the chosen model. The Integrated DRASTIC GIS-based Model takes in reclassified raster factors as the independent variables, while the weights from the overall rankings were applied as weights using ArcGIS Weighted Overlay tool (Figure 4), this enables simulation of different factors in creating vulnerability map based on different criteria. The process was performed for all the datasets to achieve the final weighted output known as the vulnerability map.

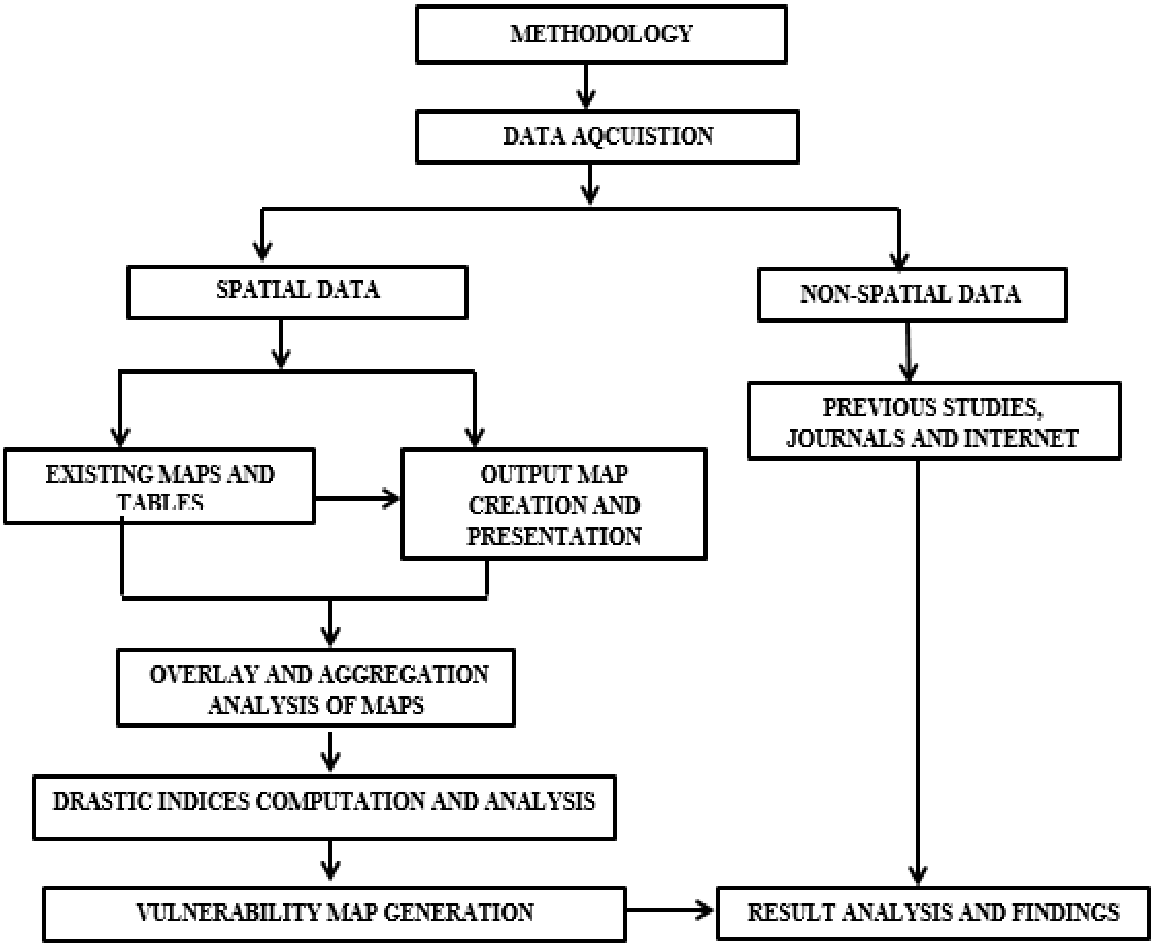

Figure 3: Study process schema

2.4.1 The Drastic Indices

2.4.4.1 Depth to Water

The depth to water factor refers to the actual depth from the ground surface to the water table. The depth of water is important because it determines the thickness of material that a contaminant would have to pass through to reach the aquifer. Generally, the thicker the material between the surface and the water table provides a higher chance of the contaminant breaking down before it can affect the aquifer. In this study, depth to groundwater table was obtained by subtracting the ground surface elevation from the average groundwater level of observation wells.

2.4.1.2 Net Recharge

The primary source of groundwater typically is precipitation which infiltrates through the surface of the ground and percolates to the water table. Net recharge represents the amount of water per unit area of land which penetrates the ground surface and reaches the aquifer. Net recharge is usually calculated by the following equation:

Net Recharge = Precipitation – Evaporation – Run Off.

Because the major underground water resource volume in the zone is replenished with lateral runoff, the recharge map was constructed according to the following formula:

Recharge value = Slope (%) + Rainfall +Soil permeability

2.4.1,3 Aquifer Media

Aquifer media refers to the characteristics of the bedrock that serve as an aquifer. An aquifer is rock below the surface that has capacity to hold water for use. The water is contained within pore spaces and cracks in the rock layer. The media of the rock affects the flow of water through the rock which also affects the rate and direction that a contaminant flows. Based on available geological cross sections from the geological map of the study area, the aquifer media map was generated.

2.4.1.4 Soil Media

Soil media refers to the portion of the earth located between the surface and the uppermost bedrock. This area contains significant biologic activity and organic material at the surface. The type and size of the soil media directly affects the rate of infiltration of pollution. Based on available soil map, the soil descriptions were used to generate and assign DRASTIC ratings to all soil types in the study area.

2.1.4.5 Topography

Topography is variability of the slope, or gradient, of the ground surface. Slope affects the type and amount of soil at the surface of the land as well as the rate and quantity of runoff. A contaminant introduced on a steep slope has less chance of infiltrating into the surface and would likely flow downward leaving concentrated pollution at the base of the slope near a groundwater source. Slope is also used to determine gradient and flow of the water table since the water table similarly follows the contour of the surface. Slope information was acquired from DEM of the study area. The DEM was extracted from SRTM 30m Digital Elevation Model database. The rating distribution map of topography slopes is also shown.

2.4.1.6 Impact of the Vadose Zone

The vadose zone is defined as the unsaturated zone above the water table. The vadose zone consists of the material existing as the surface soil, as well as the bedrock layers without a holding capacity for ground water. The impact of pollution on the vadose zone is measured based on the thickness, porosity, and permeability of all material within the vadose zone. The ratings are assigned per the influence of the least impervious material, taking into account all types of material toward the surface.

2.4.1.7 Hydraulic Conductivity

Hydraulic conductivity refers to the rate at which the aquifer materials transmit water. The rate is affected by the material, porosity, and gradient of the aquifer. Hydraulic conductivity is important because it determines the rate of movement through the aquifer of a contaminant from the point of contact. Higher rates represent higher susceptibility to contamination (Klug, 2009). For the study area, the values of hydraulic conductivity were obtained from field data.

DRASTIC evaluates contamination potential based on the above seven hydrogeological settings (Aller *et al.*, 1987). Each factor is assigned a weight based on its relative significance in affecting the pollution potential. Each factor is further assigned a rating for different ranges of values. The typical ratings range from 1 - 10 and weights are from 1 – 5 as contained in Table 1.

The DRASTIC Index, a measure of contamination potential is computed by summation of the products of ratings and weights for each factor as follows (Aller *et al.*, 1987):

DRASTIC Index = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw (1)

Where:

Dr = Ratings to the depth to water table
Dw = Weights assigned to the depth to water table
Rr = Ratings for ranges of aquifer recharge
Rw = Weights for the aquifer recharge
Ar = Ratings assigned to aquifer media
Aw = Weights assigned to aquifer media
Sr = Ratings for the soil media
Sw = Weights for soil media
Tr = Ratings for topography (slope)
Tw = Weights for topography
Ir = Ratings assigned to vadose zone
Iw = Weights assigned to vadose zone
Cr = Ratings for rates of hydraulic conductivities
Cw = Weights given to hydraulic conductivity

Equation 2 is a summarised version of equation 1, which was used in the evaluation of the factors.

$$V = \sum_{i=1}^{7}(W_i \times R_i) \quad (2)$$

Where: V, is the index value and W_i is the weighted coefficient for parameter *i*, with an associated rating value of R_i.
The higher the DRASTIC index, the greater the relative contaminant is to the water sources. The DRASTIC index can be further divided into four categories as: low, moderate, high, and very high.

Table 1: DRASTIC rating system and weights Adapted from (Klug, 2009)

SN		Range	Rating	Weight
1	**Depth To Water Table (Feet)**	0-5	10	5
		5-15	9	
		15-30	7	
		30-50	5	
		50-75	3	
		75-100	2	
		100+	1	
2	**Net Recharge (Inches)**	0-2	1	
		2-4	3	4
		4-7	6	
		7-10	8	
		10+	9	
3	**Aquifer Media**	Massive Shale 1	2	3
		Metamorphic	3	
		Igneous 2-5	4	
		Weathered Metamorphic/Igneous 3-5	5	
		Glacial Till 4-6	6	

		Bedded Sandstone, Limestone & Shale Sequences 5-9	6	
		Massive Sandstone 4-9	8	
		Massive Limestone 4-9	8	
		Sand and Gravel 4-9	9	
		Basalt 2-10	10	
		Karst Limestone 9-10		
4	**Soil Media**	Thin or Absent	10	2
		Gravel	10	
		Sand	9	
		Peat	8	
		Shrinking and/or Aggregated Clay	7	
		Sandy Loam	6	
		Loam	5	
		Silty Loam	4	
		Clay Loam	3	
		Muck	2	
		Non-Shrinking and Non-aggregated Clay	1	
5	**Topography (Slope)**	0-2	10	1
		2-6	9	
		6-12	5	
		12-18	3	
		18+	1	
6	**Impact Of Vadose Zone**	Confining Layer 1	1	5
		Silt/Clay 2-6	3	
		Shale 2-6	3	
		Limestone 2-5, Sandstone 2-7	3	
		Bedded Limestone, Sandstone, Shale 4-8	6	
		Sand and Gravel with significant Silt and Clay 4-8	6	
		Sand and Gravel 4-8, Basalt 2-10	6	
		Karst Limestone	8	
7	**Conductivity (Hydraulic)**	1-100	1	3
		100-300	2	
		300-700	4	
		700-1000	6	
		1000-2000	8	
		2000+	10	

2.4 Vulnerability Analysis

A multiplier (importance weight) was assigned to each parameter to reflect the relationship among the parameters and their importance for vulnerability/impact assessment. Each of the selected parameters has a given range, which is subdivided into discrete hierarchical intervals. Each interval was assigned a value reflecting the relative degree of vulnerability, and the rating points were summed. The final numerical score will be divided into segments (mapping) expressing a relative vulnerability degree. Geographic Information System (GIS) technique was integrated with the index and overlay method of DRASTIC model, to produce a vulnerability map for the area of study. Each hydrogeology setting is defined as a map-able unit with common hydro-geologic characteristics. The model employs a numerical ranking system that assigns relative weights to various parameters that help in evaluating of relative groundwater vulnerability to contamination.

2.5 Datasets Sources and Layer Creation

The research workflows involved the integration of primary and secondary data sources, and spatial analytical models. GIS datasets used include borehole coordinates, existing roads, waterbodies/rivers, slope, topography and geological data, settlement data, and remotely sensed data such as Landsat 8 imagery. The various data types used for this research and their respective sources are given in Table 2. Figure 4, shows the data processing procedure in Arc GIS software environment.

Table 2: Research data sources

S/n	Data type	Sources	Format	Expected output layer
1.	Borehole Data (Water Table Level) and their coordinates	Geological Services Dept. Min. of Energy & Mineral Resources.	Table	Depth of Water map (D)
2.	Average Annual Rainfall	Office of The Surveyor General, Lagos State.	Map	Net Recharge map(R)
3.	Geological Map	Nigeria Geological Survey Agency	Map	Aquifer map (A)
4.	Soil Map	Office of The Surveyor General, Lagos State	Map	Thematic Soil map (S)
5.	Digital Elevation Model	Shuttle Radar Topography Mission (SRTM) by NASA	Raster model	Thematic Topography map (T)
6.	Geologic Profile	Geological Services Dept. Min. of Energy & Mineral Resources.	Map	Vadose zone (I)
7.	Conductivity	Geological Services Dept. Min. of Energy & Mineral Resources.	Table	Conductivity map (C)
8.	Landsat 8 Image	United States Geological Surveys (USGS)	Raster	Land use land cover

Table 3: GIS Data layers and the assigned rules

S/n	Data	Dataset	Factors
1.	Digitized Road	Road Network	Roads
3.	Digitized Rivers	Land cover classes	Rivers/Hydrogeology
4.	SRTM Data	DEM/Slope data Rocks raster	Terrain/topography/Depth
6.	Landsat Imagery	Land use land cover classes	Urban areas
8.	Geological Map	Rocks raster	Surface geology

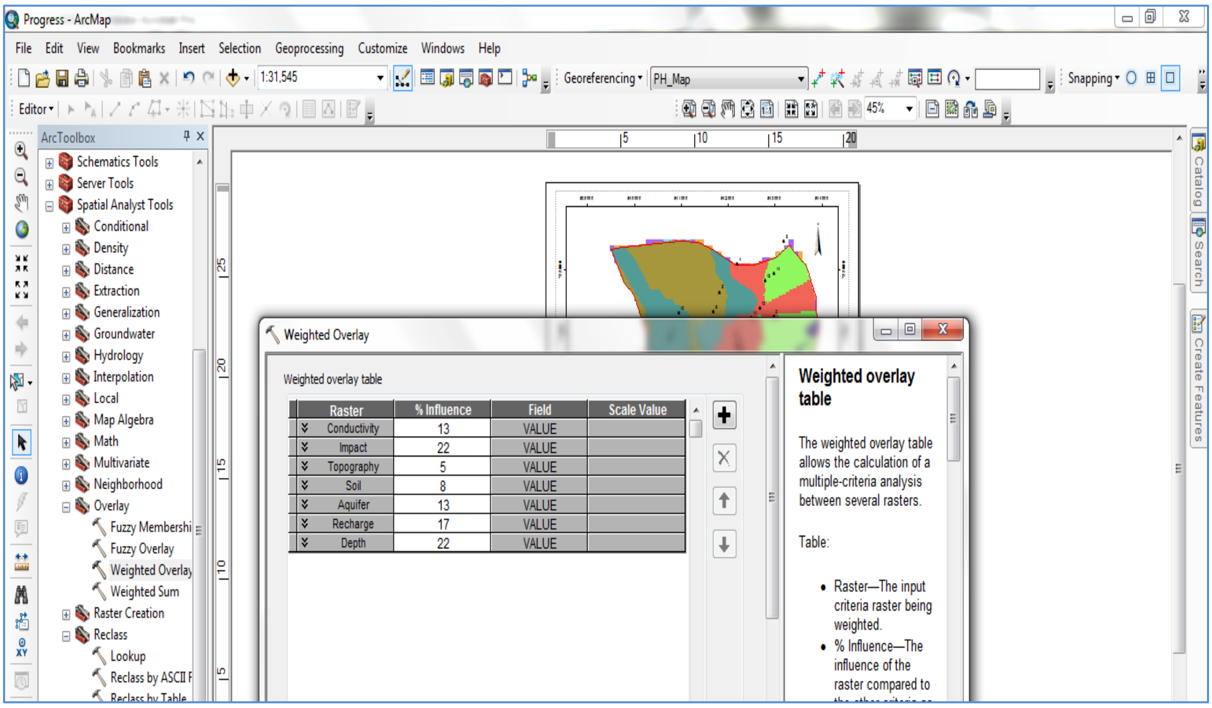

Figure 4: Weighted Overlay

3.0 Results and Discussion

This section shows the results and discussion of the findings from the processing of both the spatial and non-spatial data acquired for this study. Maps of various result were presented.

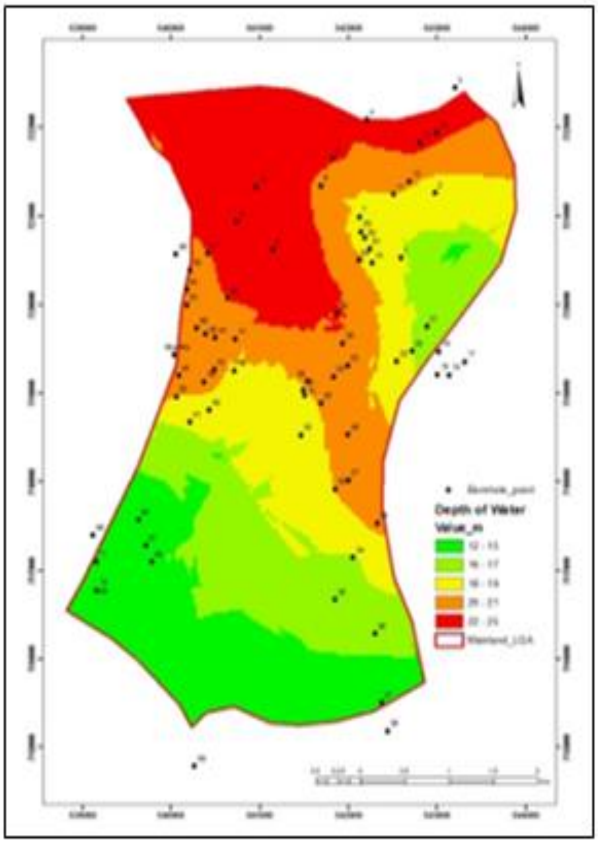

Figure 5a: Depth to Water

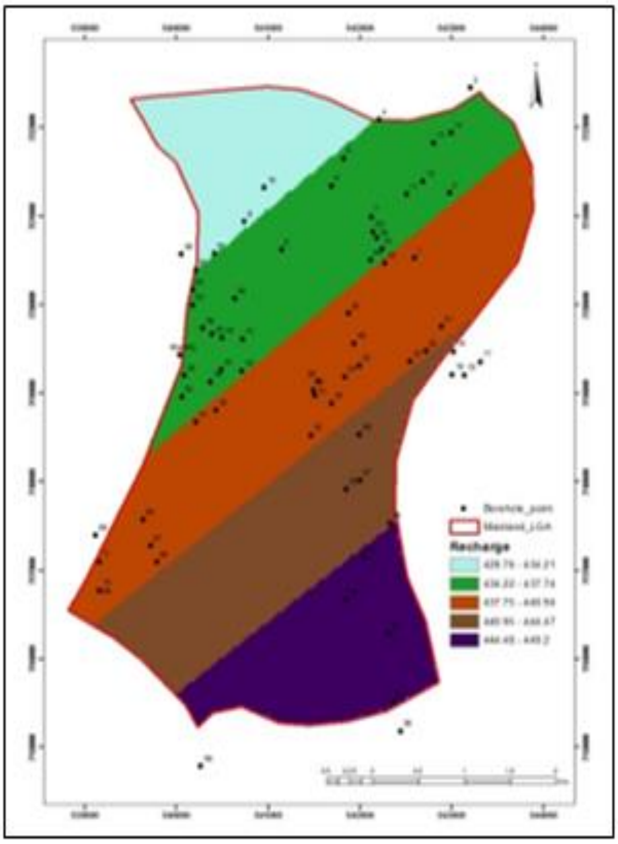

Figure 5b: Net Recharge Map

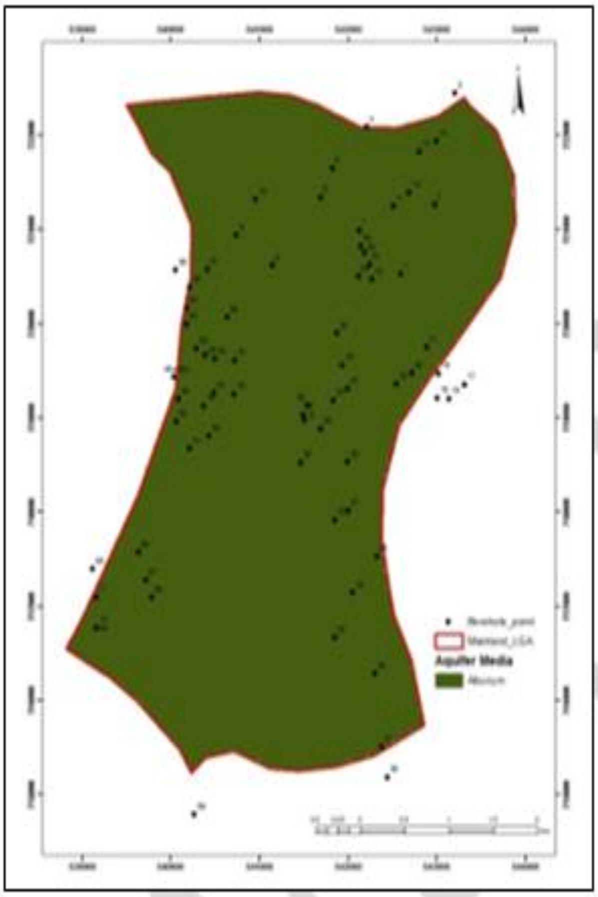

Figure 5c: Aquifer Media Map

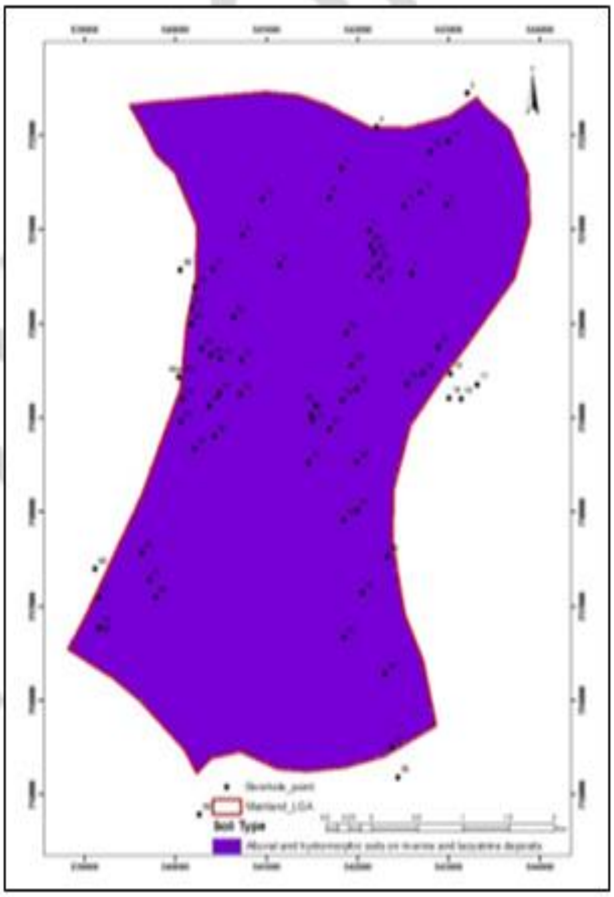

Figure 5d: Soil Map

The depth to water was achieved using the Kriging interpolation tool of ArcGIS Geostatistical Analyst extension to interpolate the points and to develop the raster map with a pixel size of 30 m. The depths to the water levels are classified into five classes: 12–15m, 16–17m, 18 – 19m, 20-21m and 22 - 25m, with depth to water rates of 10, 8, 6, 4, and 2, respectively. The resultant map is shown in Figure 5a.

The net recharges map. The recharge values observed in the study area ranges from 428.76 to 449.20. The ratings assigned to net recharge in the study area were presented in Table 1 and the spatial variation is shown in Figure 5b.

The Aquifer media map. Based on the geological map of South-West Nigeria, the aquifer media map was generated by overlaying it on the map of the study area. The aquifer media of the Lagos mainland was identified as alluvium. The resultant map is as shown in Figure 5c.

Soil map of study area. The soil map of the study area was generated overlay analysis with the soil map of Nigeria. The study area is characterized by Alluvial and hydromorphic soils on riverine and lacustrine deposits. The soil map is shown in Figure 5d.

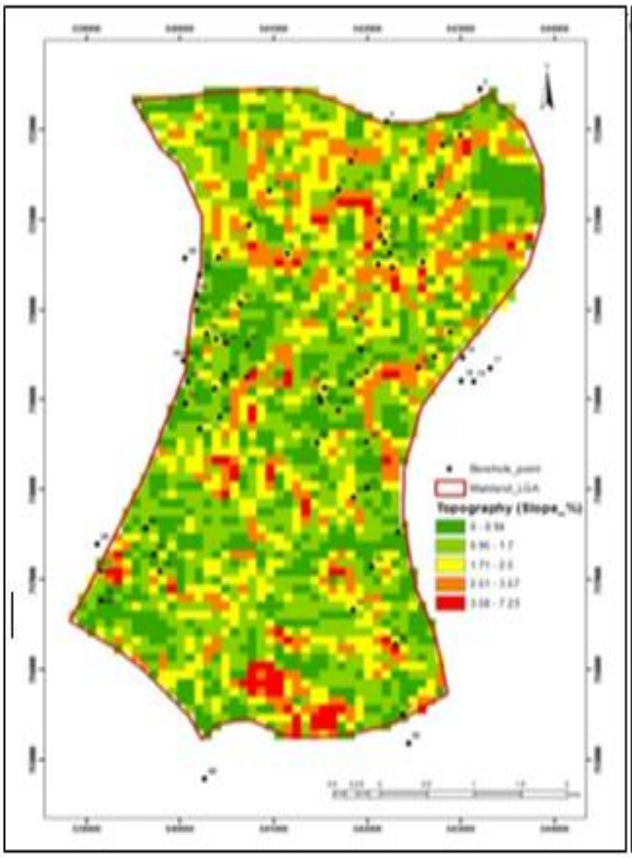

Figure 5e: Slope Map

Figure 5f: Impact of the Vadose zone map

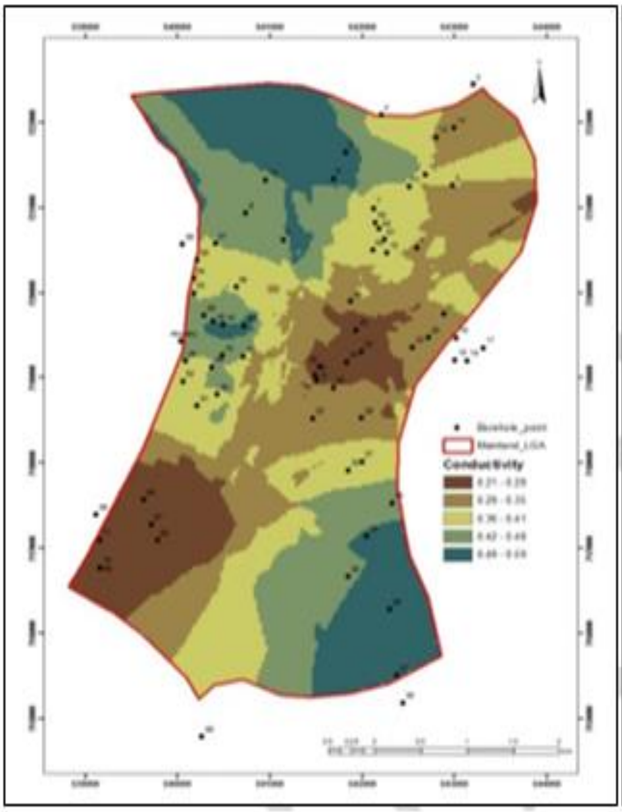

Figure 5g: Hydraulic Conductivity Map 1

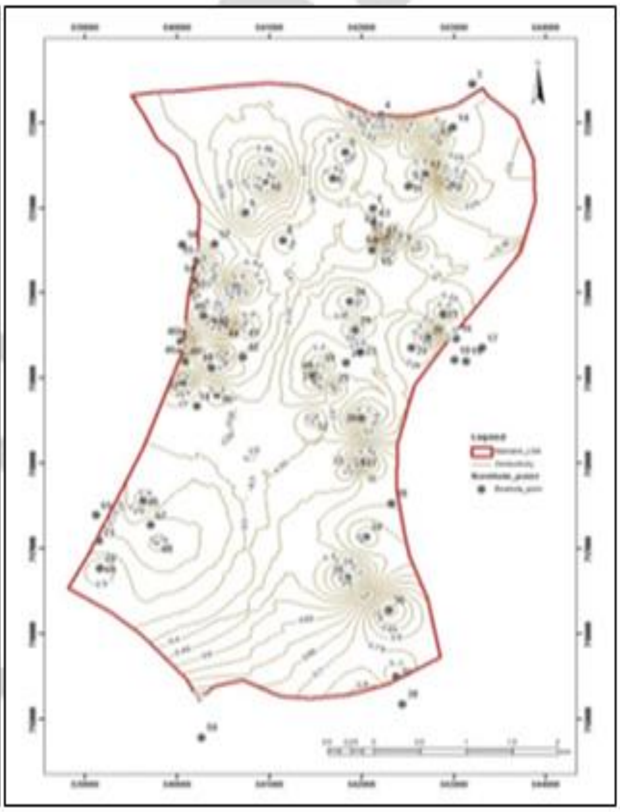

Figure 5h: Hydraulic Conductivity Map 2

Figure 5e shows the slope map for the study was produced from the digital elevation model (DEM) of the study area and was used to identify the slope (%) and soil permeability was calculated from soil type. Average rainfall of the study area was used as a recharge index and the finalized recharge value was calculated and the ratings were assigned.

The vadose zone refers to the zone above the water table, which is unsaturated and its type determines the attenuation characteristics of the material including the typical soil horizon and rock above the water table. For the study area, alluvium is considered the vadose zone as shown in Figure 5f.

The hydraulic conductivity distribution map was generated using pumping test results gathered from the geo-electrical study of the area. Regions with maximum hydraulic conductivity exhibited higher chances of distribution contamination. Hydraulic conductivity was derived by measurement, and the GIS-ArcMap was used to interpolate the hydraulic conductivity which was used to create the raster and topographical maps in Figures 5g and 5h respectively.

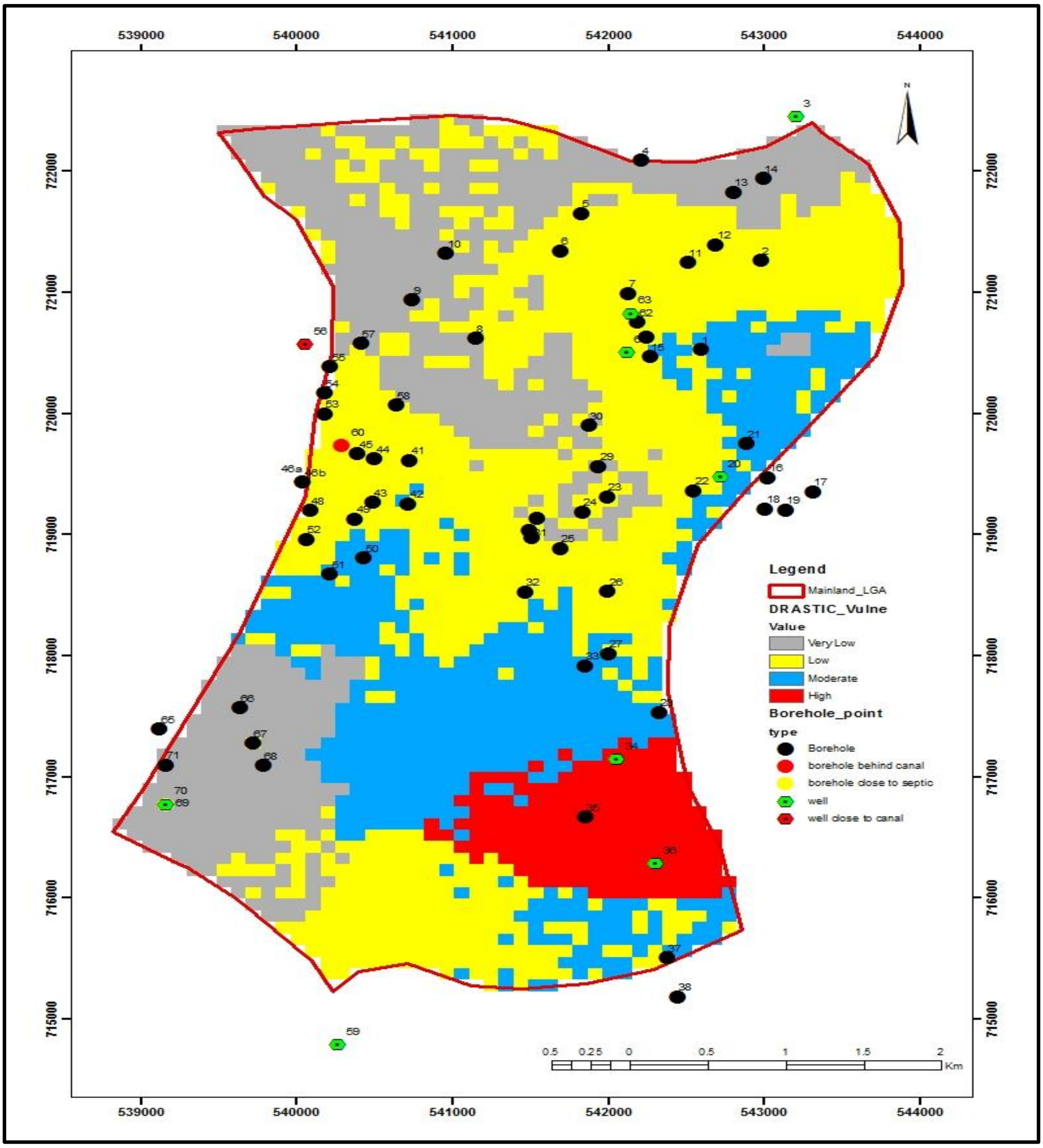

Figure 6: Groundwater Susceptibility Map of Lagos Mainland

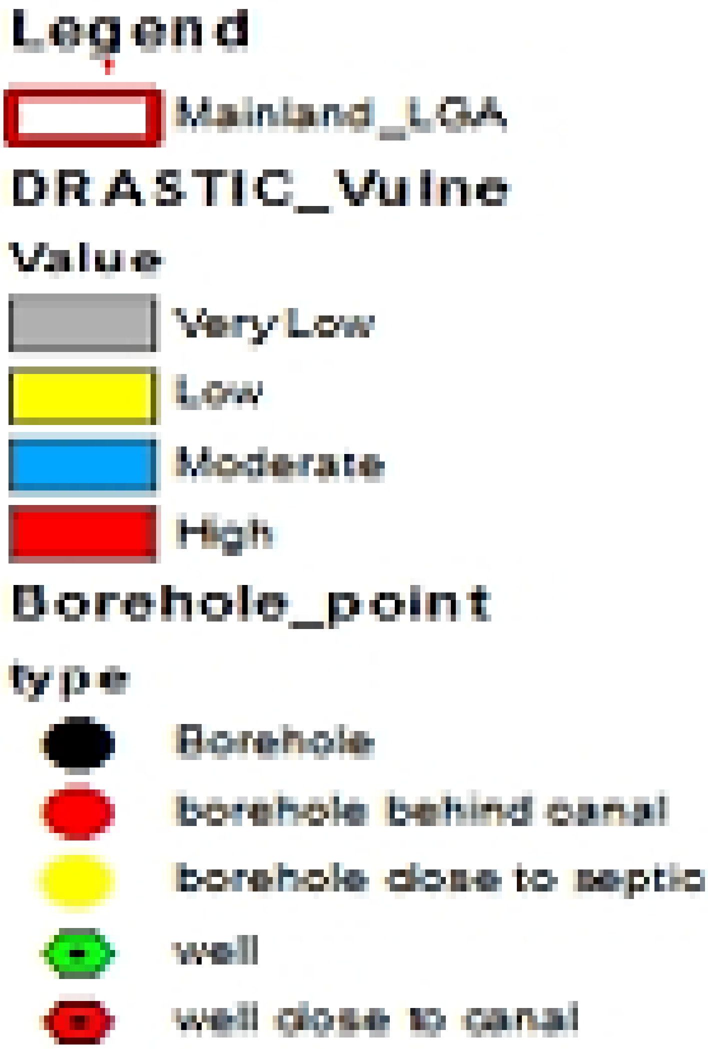

Figure 6b: Legend of susceptibility map expanded

Figure 6a shows the groundwater contamination susceptibility map of Lagos Mainland and Figure 6b is the expansion of the legend to make the susceptibility information clearer. The map indicated four zones represent with different colour for susceptibility rating. The area in red indicated "High susceptibility" estimated to be about 18% confined at the south-eastern part of the map which means that the groundwater in the areas have high cases of boreholes or well dug close to canals and septic tanks. The implication of this is that the tendency for groundwater to be contaminated in these locations are very high respectively. The areas in blue shows "Moderate susceptibility" estimated to be about 25%, These areas are seen in north-eastern, middle, and part of the south-eastern part of the map. The implication is that the tendency of the groundwater to be polluted in moderate as the boreholes and wells found around these areas are further away from septic tanks and canals resulting to moderate level of groundwater contamination risk. The areas in Yellow reveals "Low susceptibility", which means about 28% chances of groundwater contamination risk is expected in the northern and south-eastern part of the map due to boreholes and wells location within these areas. The areas in ash colour indicates "Very low susceptibility", estimated to be about 29%. The implications as observed from the map suggests that these areas are the safest in term of exposure to the risk of groundwater contamination.

4.0 Conclusion

In this research an attempt has been made to assess aquifer vulnerability in the Lagos Mainland. The major causes of groundwater contamination risk are the presence of contaminants, such as waste deposits from industries and other human activities. The vulnerability of groundwater to contamination in the study area was quantified using the integration of DRASTIC model and GIS. The vulnerability index of the area indicates that groundwater resources in the surrounding area are susceptible to pollution to a moderate degree by the presence of contaminants. The vulnerability map has a range from the highly vulnerable to contamination to the very low vulnerable. It has been shown from the study that a GIS-based DRASTIC index model is adequate and suitable for planning and mapping of groundwater vulnerability. Safer and cheaper water resources management is a major concern for the government and masses (Ukpaka and Ukpaka, 2016). Having built a database that includes topography, geology and Land Use/Land Cover from available maps and satellite imagery for the study area, additional data such as rainfall and other climatic factors data can also be incorporated to modify the model. Vulnerability maps do not replace more detailed studies of the geological and hydrogeological conditions of particular sites for the envisaged use. Since the world is not stagnant and development occurs regularly, the model generated in this study is dynamic and other factors that were not considered can be incorporated to achieve better results. However, this model can still be implemented in the development of water resources management.

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